Interval – Valued Neutrosophic Sets to Develop Multi – Criteria Decision Making Approach for Renewable Energy Selection

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Abstract. Due to lack of indigenous conventional energy resources, renewable energy has become a potential alternative for Taiwan’s future energy supply. Numerous studies have recently emerged on renewable issues in Taiwan. However, studies that specifically consider effects of various influential parameters on evaluation and selection of renewable energy sources based on multi-criteria decision making (MCDM) method are still limited to some specific part of the renewable energy sources (RES). MCDM methods has become increasingly popular in solving the decision-making problems which involve multiple criteria. This study proposes an extension of MCDM approach to evaluate renewable energy sources, using the combination of Analytic Hierarchy Process (AHP) method with the Order Performance technique, based on Similarity to Ideal Solution (TOPSIS) method under neutrosophic environment.

Keywords. MCDM approach, renewable energy sources, neutrosophic sets, AHP method, TOPSIS method.

Introduction

Energy plays an important role in the economic development, especially after energy crisis in 1970s [1]. Because of the characteristics of cleanliness to environment and inexhaustible nature, renewable energy development becomes an important issue for many countries to address sustainable energy supply and overcome the anthropogenic negative impacts on the environment of fossil fuels [2, 3].

Taiwan, which is located in a low-latitude zone with outstanding benefits of the potential wind capacity, renewable energy sources (RES) have become more attractive to be developed [3]. Despite the enormous RES, the usage of renewable energy still remains a small portion. One of the key factors for this limitation is the high investment cost and the low return on investment compared to the conventional energy [2, 3]. Therefore, it is necessary to consider thoroughly the impact of many factors such as financial, economic, environmental and technical perspective, to the evaluation and selection of the most appropriate RES [4]. Multi-criteria decision making (MCDM) approach has become popular in the field of energy because of the flexibility that it provides to make appropriate decisions with conflicting and multiple criteria [4, 5]. Five

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RES including Hydropower, Solar power, Wind power, Biomass power and Geothermal power are being considered as alternatives in this paper.

The combination of MCDM techniques and fuzzy set theory (as known as fuzzy MCDM) has been widely accepted and became the most commonly techniques in RES selection [3]. Fuzzy set can handle incomplete information. However, Fuzzy set can not deal with the indeterminate information and inconsistent information [6-12]. In practice, the information for decision is often incomplete, indeterminate and inconsistent [9]. Therefore, the combination of MCDM techniques and fuzzy set is not an effective approach. To deal with this disadvantage of fuzzy set, Smarandache [13] further proposed the neutrosophic set by adding an independent indeterminacy membership on the basis of fuzzy set [9].

Recently, neutrosophic sets has become an interesting research topic and attracted widely attentions [7-9, 11, 12]. The combination of neutrosophic sets and MCDM approach has been successfully applied in different fields to solve problems as low-carbon supplier selection [14], supplier selection [15], evaluation of e-commerce websites [16], outsourcing provider selection [17], but in energy source selection field, it is still remains a small portion.

Moreover, the degree of truth, falsity and indeterminacy of a certain statement cannot be defined precisely in real situations, therefore Wang [18] proposed an interval–valued neutrosophic sets (IVNSs) to overcome this difficulty. In this study, an extension of MCDM approach using interval–valued neutrosophic sets is proposed to evaluate RES in Taiwan. Under neutrosophic environment and AHP process, the weights of criteria are assessed in linguistic terms represented by interval–valued neutrosophic numbers. Then, these values are averaged into a comparable scale. Next, the weighted ratings of alternatives are also derived by interval–valued neutrosophic numbers. Finally, by using Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) technique, through the relative closeness coefficient, alternatives will be evaluated and ranked.

1. Literature review

The combination of MCDM models and fuzzy theory has been extensively used in ranking renewable energy alternatives, which has got a series of achievements. For instance, Kahraman and Kaya [19] employed applied AHP method under fuzziness environment (FAHP) to select the best energy policy for Turkey from four perspectives (Technology, Environment, Socio–Political, Economic) and 17 sub-criteria. At the end, wind energy was determined as the best energy policy alternative for in Turkey. Similarly, Tasri and Susilawati [20] based on a FAHP method to determine the best renewable energy sources for electricity generation for inIndonesia. With the highest final score, the hydro power was found to be the best energy source for this country, followed by geothermal, solar, wind energy and biomass. Kaya, Kahraman and San Cristóbal [19, 21-23] combined AHP method and VIKOR method to determine the best renewable energy alternative for Istanbul City and Spanish. Yazdani-Chamzini et al [24] used an integrated AHP process and COPRAS method including VIKOR, SAW, TOPSIS, ARAS and MOORA to select the best renewable energy project. They compared the model with these five MCDM tools to validate the output of the proposed model. Wu et al., [4] presented a FAHP model which based on the cumulative prospect theory to help public investors in choosing the most appropriate RES. With 14 sub–

criteria from economical, environmental, socio-political and technical aspect, solar PV was selected the best RES for China. Çolak and Kaya [25] employed the AHP method using interval type-2 fuzzy sets and hesitant fuzzy TOPSIS methods to evaluate renewable energy alternatives for Turkey. The results showed that the Economic criterion is determined as the most important criterion among main criteria with the highest weight, and the wind energy was determined as the best renewable energy alternative for Turkey with the best relative closeness value.

After being proposed in 1999, neutrosophic sets have been applied in many field since 2013, one of the applications is decision making process, namely neutrosophic MCDM approach [7]. From literature, AHP and TOPSIS are used the most commonly in MCDM process, however, the combination of AHP method and TOPSIS method under neutrosophic environment is still a blank area [25].

Recently, there are some studies proposing the models that used one of these two methods with neutrosophic sets. For instance, Ye [26] suggested entropy and similarity measures of single valued neutrosophic set and interval–valued neutrosophic set, respectively. Similarly, Tian [10] also developed the MCDM approach based on a cross entropy with interval–valued neutrosophic sets and examined its characteristics with the example of an investment appraised project. Ye [11] also proposed methods for solving MCDM problems using a cross-entropy and correlation coefficient. Pingping Chi [9] proposed a novel concept about TOPSIS method for the multiple attribute decision making problems in which the attribute weights are unknown and attribute values take the form of Interval–valued neutrosophic sets. There are three studies applying neutrosophic AHP methods to solve the problems [7, 15, 27]. Radwan et al., [27] developed a novel hybrid neutrosophic AHP method in learning management systems in decision making. Abdel et al., [15] developed the integration of AHP into Delphi framework under neutrosophic environment and introduced a new technique for checking consistency and calculating consensus degree of expert's opinions. Meanwhile, Bolturk and Kahraman [7] presented two methods which are AHP and the combination of AHP with cosine similarity measure under interval neutrosophic environment.

Therefore, in this paper, an extension of MCDM approach using the combination of AHP and TOPSIS method under interval–valued neutrosophic sets is proposed for evaluating the most appropriate RES in Taiwan. This case study in Taiwan is carried out to illustrate the rationality and feasibility of the proposed method.

2. Methodology

2.1. Evaluation criteria system

Criteria and the sub–criteria system is one of the factors playing an important role in the RES selection process. In this paper, four main criteria is selected to analyze including Technical, Economical, Environmental and Socio–Politics aspects. Sub-criteria associated with each criterion were also identified from literature and expert's opinion. Figure 1 is the evaluation criteria system in this paper.

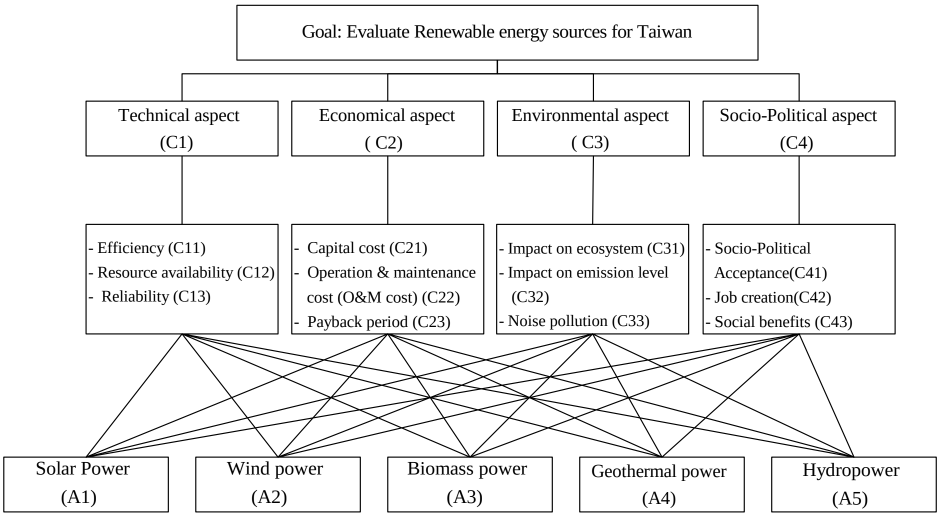

Figure 1. The evaluation criteria system of RES

These sub–criteria can be briefly summarized as follow:

- C11: Efficiency: This criterion is used to explain how much useful energy extracted from an energy source.
- C12: Resource availability: This criterion measures the availability of renewable energy resources to generate energy.
- C13: Reliability: This criterion indicates the ability of a system to operate within designed conditions.
- C21: Capital cost: This criterion refers to the total cost in establishing a power plant, includes the equipment, labor, installation cost, …
- C22: Operation and maintenance cost (O&M cost). This criterion includes two components: Operation costs, including salaries additional to the expenditure on energy production and services and maintenance costs are the funds spent to ensure reliable plant operations and to avoid failure and damage.
- C23: Payback period. This criterion is the period of time that is necessary to compensate the original cost of renewable energy plant.
- C31: Impact on ecosystem. This criterion is used to measure the disturbance of power plant on ecosystem.
- C32: Impact on emission level. This criterion refers to the impact of a power plant on the environment and society in terms of emission reduction.
- C33: Noise pollution. This is the criterion which indicates the impact of noise from a power plant on the environment.
- C41: Socio - Political Acceptance. This criterion reflects the consensus among government and other social partners for the proposed power plant.
- C42: Job creation. This criterion evaluates how many people the power projects can employ in their cycle life, from construction to decommissioning.
- C43: Social benefits. This criterion represents the social progress in the local community and region by initiating a power project.

2.2. Neutrosophic sets and interval–valued neutrosophic sets

Neutrosophic sets is a powerful general formal framework which generalizes the concepts of classic set, fuzzy set, interval–valued fuzzy set, intuitionistic fuzzy set, etc [11]. Based on fuzzy sets, F. Smarandache [13] added indeterminacy membership function in neutrosophic set, with the truth membership function and falsity membership function of intuitionistic fuzzy sets to handle incomplete, indeterminate and inconsistent information in real life [9].

Definition 1: Pingping Chi [9] Let X be a universe of discourse, with a generic element in X denoted by *x*. A neutrosophic set (NS) A in X is $A(x)=(T_A(x),I_A(x),F_A(x))$ where $T_A(x),I_A(x),F_A(x)$ are respectively the truth–membership function, indeterminacy–membership function, and the falsity–membership function. $T_A(x),I_A(x),F_A(x)$ are real standard or nonstandard subsets of $[0^-,1^+]$.

There is no restriction on the sum of $T_A(x),I_A(x)$ and $F_x(x)$ so $0^- \le T_A(x)+I_A(x)+F_A(\mathrm{x}) \le 3^+$.

Then, Wang [18] proposed Interval–Valued Neutrosophic Sets, which can express three of membership functions in interval numbers, instead of crisp numbers.

Definition 2: Wang [18] Let X be a universe of discourse, with a generic element in X denoted by *x*. A neutrosophic set A in X is $A=\{x(T_A(x),I_A(x),F_A(x)) \mid x\in X\}$ where $T_A(x),I_A(x),F_A(x)$ are respectively the truth–membership function, indeterminacy–membership function, and the falsity–membership function. For each point x in X, we have that $T_A(x)=\left[inf\ T_A\left(x\right), sub\ T_A\left(x\right)\right]$, $I_A(x)=\left[inf\ I_A\left(x\right), sub\ I_A\left(x\right)\right]$, $F_A(x)=\left[inf\ F_A\left(x\right), sub\ F_A\left(x\right)\right] \subseteq [0^-,1^+]$. There is no restriction on the sum of $T_A\left(x\right),I_A\left(x\right),F_A\left(x\right)$ so $0^- \le subT_A\left(x\right)+subI_A\left(x\right)+subF_A\left(x\right)\le 3^+$.

For convenience, we can use $x=\left(\left[T^L,T^U\right],\left[I^L,I^U\right],\left[F^L,F^U\right]\right)$ to represent a value in Interval–Valued Neutrosophic Sets [9].

The Operational Rules of the Interval–Valued Neutrosophic Sets:
Let *x* and *y* are two Interval–Valued Neutrosophic Numbers, in which
$x=\left(\left[T_1^L,T_1^U\right],\left[I_1^L,I_1^U\right],\left[F_1^L,F_1^U\right]\right)$, $\mathrm{y}=\left(\left[T_2^L,T_2^U\right],\left[I_2^L,I_2^U\right],\left[F_2^L,F_2^U\right]\right)$

$$\begin{aligned} x\oplus y=\Big(&\left[T_1^L+T_2^L-T_1^L\times T_2^L, T_1^U+T_2^U-T_1^U\times T_2^U\right],\\ &\left[I_1^L\times I_2^L, I_1^U\times I_2^U\right],\left[F_1^L\times F_2^L, F_1^U\times F_2^U\right]\Big) \end{aligned} \quad (1)$$

$$x \otimes y = \left(\left[T_1^L \times T_2^L, T_1^U \times T_2^U \right], \left[I_1^L + I_2^L - I_1^L \times I_2^L, I_1^U + I_2^U - I_1^U \times I_2^U \right] \right.$$
$$\left. \left[F_1^L + F_2^L - F_1^L \times F_2^L, F_1^U + F_2^U - F_1^U \times F_2^U \right] \right) \tag{2}$$

$$nx = \left(\left[1-\left(1-T_1^L\right)^n, 1-\left(1-T_1^U\right)^n \right], \left[\left(I_1^L\right)^n, \left(I_1^L\right)^n \right], \left[\left(F_1^L\right)^n, \left(F_1^L\right)^n \right] \right) \tag{3}$$
$$(\mathrm{n} \succ 0)$$

3. MCDM approach

To evaluating renewable energy sources in Taiwan, an extension of MCDM approach using the combination of AHP method and TOPSIS method under neutrosophic environment will be proposed as in Fig. 2. In the first step of the proposed model, an expert team is formed with three experts in energy sector.

Table 1: Linguistic terms and neutrosophicated strong weights

Linguistic term	Neutrosophic sets
Absolutely Strong	[1, 1], [0, 0],[0, 0]
Very Strong	[0.75, 0.85], [0.1, 0.2], [0.15, 0.25]
Fairly Strong	[0.55, 0.75], [0.2, 0.4], [0.25, 0.45]
Exactly Equal	[0.5, 0.5], [0.5, 0.5], [0.5, 0.5]
Absolutely Weak	[0, 0], [0, 0], [1, 1]
Very weak	[0.15, 0.25], [0.1, 0.2], [0.75, 0.85]
Fairly weak	[0.25, 0.45], [0.2, 0.4], [0.55, 0.75]

After selecting the alternatives and the most appropriate criteria and sub–criteria from references and expert’s opinions, we will calculate the weights for decision criteria. From the literature, this step may be obtained by many techniques, one of which is the AHP method. It constructs pair-wise comparisons for a set of criteria to judge the relative importance of one criteria to another or one sub–criteria to the others from the judgments of three experts through linguistic variables given in Table 1. In this paper, the AHP method the using Interval–Valued neutrosophic numbers concept adapted from [7].

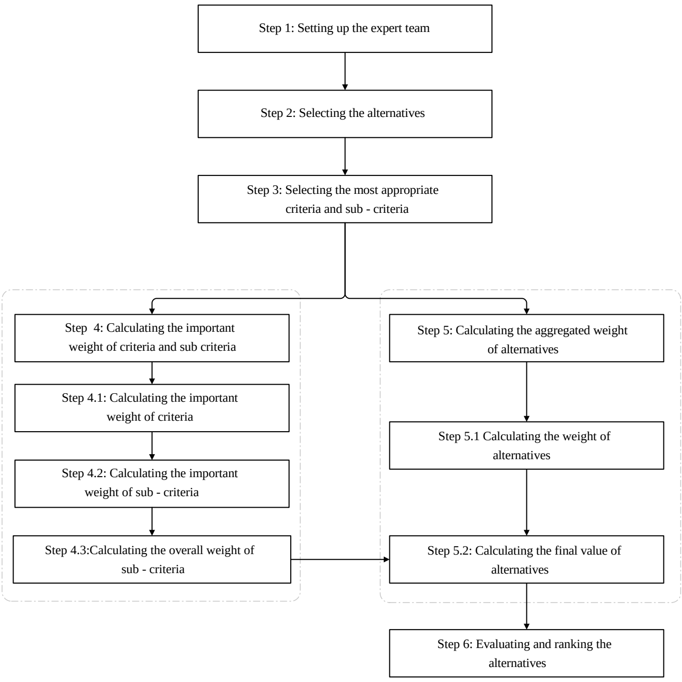

Figure 2. Decision framework of renewable energy evaluation

Then we will use Eqs. (1)-(3) in the operations of Interval–Valued Neutrosophic Sets to calculate the value of alternatives. Finally, TOPSIS method will be utilized to evaluate and ranking the alternatives. TOPSIS is one of the most common multi-criteria decision making techniques, which was initially developed by Hwang and Yoon [1]. This technique evaluates alternatives according to their distance values to ideal solution (Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS)), and relative closeness coefficient of each alternative is calculated by means of these values from the previous step.

The basic principle of TOPSIS technique is that the best alternative should have the shortest distance to the positive ideal solution and the farthest distance to the negative ideal solution [9]. Thus, the smaller relative closeness coefficient (RCC_i) is, the better alternative A_i is. In this context, the positive ideal solution and negative ideal solution will be defined by the [9] and all of the equations in this step are also derived this research literature.

4. Results

The proposed neutrosophic MCDM approach will be applied to solve renewable energy sources evaluation problem in this section,.

Firstly, the weights of criteria are obtained by evaluations of three experts who have experience in energy decision making problems. As a result of expert evaluations, the pairwise comparison matrices of criteria and sub–criteria are obtained. Then, this paper applies the AHP method under neutrosophic environment (NAHP) to calculate the weight of criteria and sub–criteria, which is given in Table 2.

Table 2. The weight of criteria and sub – criteria

Criteria weight		Sub – criteria weight	
C1	[0.381, 0.398], [0.199, 0.232], [0.057, 0.070]	C11	[0.531, 0.531], [0.333, 0.333], [0.071, 0.071]
		C12	[0.175, 0.223], [0.259 ,0.333], [0.381, 0.454]
		C13	[0.180, 0.245], [0.259, 0.333], [0.403, 0.475]
C2	[0.263, 0.303], [0.209, 0.287], [0.153, 0.198]	C21	[0.206, 0.275], [0.259, 0.333], [0.337, 0.420]
		C22	[0.140, 0.190], [0.259, 0.333], [0.451, 0.509]
		C23	[0.535, 0.535], [0.333, 0.333], [0.071, 0.071]
C3	[0.165, 0.198], [0.250, 0.250], [0.226, 0.243]	C31	[0.249, 0.325], [0.252, 0.350], [0.273, 0.343]
		C32	[0.206, 0.272], [0.245, 0.328], [0.335, 0.389]
		C33	[0.338, 0.403], [0.229, 0.322], [0.187, 0.268]
C4	[0.075, 0.101], [0.205, 0.231], [0.470, 0.490]	C41	[0.252, 0.336], [0.244, 0.360], [0.253, 0.339]
		C42	[0.351, 0.410], [0.232, 0.320], [0.177, 0.250]
		C43	[0.178, 0.253], [0.232, 0.320], [0.350, 0.412]

From these weights of criteia and sub–criteria, the overall weight of sub-criteria is calculated from interval neutrosophic evaluation scale method [7]. The overall weight of sub–criteria is shown in Table 3.

Table 3. The overall weight of sub – criteria

Overall Weight = CW x SCW	C11	[0.202, 0.212], [0.466, 0.488], [0.124, 0.136]
	C12	[0.067, 0.089], [0.407, 0.488], [0.417, 0.492]
	C13	[0.069, 0.098], [0.407, 0.488], [0.437, 0.512]
	C21	[0.054, 0.083], [0.414, 0.524], [0.439, 0.534]
	C22	[0.037, 0.058], [0.414, 0.524], [0.535, 0.606]
	C23	[0.141, 0.162], [0.473, 0.524], [0.213, 0.254]
	C31	[0.041, 0.064], [0.439, 0.512], [0.437, 0.503]
	C32	[0.034, 0.054], [0.434, 0.496], [0.485, 0.537]
	C33	[0.056, 0.080], [0.422, 0.491], [0.370, 0.446]
	C41	[0.019, 0.034], [0.399, 0.508], [0.604, 0.385]
	C42	[0.026, 0.042], [0.390, 0.477], [0.564, 0.302]
	C43	[0.013, 0.026], [0.390, 0.477], [0.655, 0.453]

And then, with the judgments of three experts and overall weights of sub–criteria, Eqs. (1)-(3) are used to calculate the final value of five alternatives that is presented in **Table 4.**

Table 4: Final value of alternatives

Alternatives	Final value
Solar power (A1)	[0.039, 0.060], [0.620, 0.724], [0.555, 0.613]
Wind power (A2)	[0.036, 0.055], [0.656, 0.754], [0.596, 0.657]
Biomass power (A3)	[0.035, 0.054], [0.664, 0.761], [0.604,0.659]
Geothermal power (A4)	[0.033, 0.052], [0.681, 0.774], [0.624,0.681]
Hydro power (A5)	[0.042, 0.063], [0.595, 0.702], [0.525,0.583]

Applying TOPSIS method based on Interval–Valued neutrosophic numbers for the prioritization of alternatives in the next step, we will rank five alternatives to choose the best renewable energy sources. Then, the PIS and NIS of all alternatives under each sub-criterion and the relative closeness coefficient of each alternative are determined as follows:

Table 5: PIS, NIS and the relative closeness coefficient of each alternatives

Alternatives	D+	D-	Relative closeness coefficient	Ranking
Solar power (A1)	0.753	0.368	0.672	2

Wind power (A2)	0.775	0.359	0.683	3
Biomass power (A3)	0.780	0.359	0.685	4
Geothermal power (A4)	0.790	0.356	0.690	5
Hydro power (A5)	0.737	0.375	0.662	1

According to Table 5, the ranking of five alternatives is $A_5 \succ A_1 \succ A_2 \succ A_3 \succ A_4$. Thus, Hydropower is determined as the best energy source for Taiwan with the smallest relative closeness coefficient is 0.662. This alternative is followed by Solar power, Wind power, Biomass power and Geothermal power, respectively. Geothermal power also is determined the worst alternative for Taiwan.

5. Conclusion

Renewable energy sources have advantages over conventional energy systems in terms of environmental acceptability. As a result, Taiwan government has set a target to contribute the development of renewable energy industry. The Ministry of Economic Affair (MOEA) estimated that the target of installed capacity of renewable energy would reach 12513 MW by 2025 and further expand to 17250 MW by 2030 [28]. The evaluation of clean energy resources with many perspectives and criteria is a very important and difficult issue for government and investors.

In this paper, the model consisting of AHP and TOPSIS technique based on Interval–Valued neutrosophic sets is proposed to solve this problem. Through the advantages of combination of MCDM approach and Interval–Valued neutrosophic set, judgments from experts that have uncertain, ambiguous, indeterminate, inconsistent and incomplete information can be dealt better to evaluate energy decision making problems. 12 sub-criteria, that is identified from literature and expert's opinions, is categorized into 4 groups (technical, economical, environmental, socio–political). All of jugdments from three experts have been taken as Interval–Valued neutrosophic numbers.

The results showed that the Hydropower is determined as the best energy source for Taiwan. Additionally, Solar power, Wind power and Biomass power are determined to be the second, third and fourth, respectively and followed by Geothermal power. Thus, investment priorities can be planned according to ranking in Table 5, Hydropower should be a priority in the development of renewable energy sources, both according to the abundance of energy supply and in accordance to geographical conditions.

In the future, similar studies can be conducted under an Interval–Valued neutrosophic environment with other MCDM techniques or sensitivity analysis will be performed to deal with more complex problems. The decision–making model under dynamic procedure as well will be proposed to advance the interval complex neutrosophic logic system for forecasting problems.

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